

**P&W PROPULSION SYSTEMS STUDIES
RESULTS / STATUS**

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P&W PROPULSION SYSTEMS STUDIES

NASA FUNDED EFFORTS TO DATE

Propulsion systems studies for the High Speed Civil Transport (HSCT) were resumed in 1987 after a hiatus of 6 or 7 years. The initial NASA-sponsored efforts were funded through subcontracts under the Boeing (NAS1-18377) and Douglas (NAS1-18378) primary contracts from the Langley Research Center. The very early studies covered a wide range of cruise Mach numbers and provided performance, installation and weight information for both existing and newly-defined study engines, with the primary goal of narrowing the Mach number range to the region of interest. Later studies under these subcontracts included tasks devoted to the environmental issues of noise and stratospheric cruise emissions.

The NASA Lewis Research Center contracted directly with Pratt & Whitney for a series of studies over a three year period beginning in late 1987. These studies included evaluation of various engine cycles with a major emphasis on the airport noise reduction challenge. The current NASA-Lewis funded studies include investigation of the design trades available to achieve satisfactory life in a commercial supersonic transport application, mixed flow turbofan cycle and conceptual design studies and an axisymmetric vs two dimensional nozzle conceptual design and evaluation study.

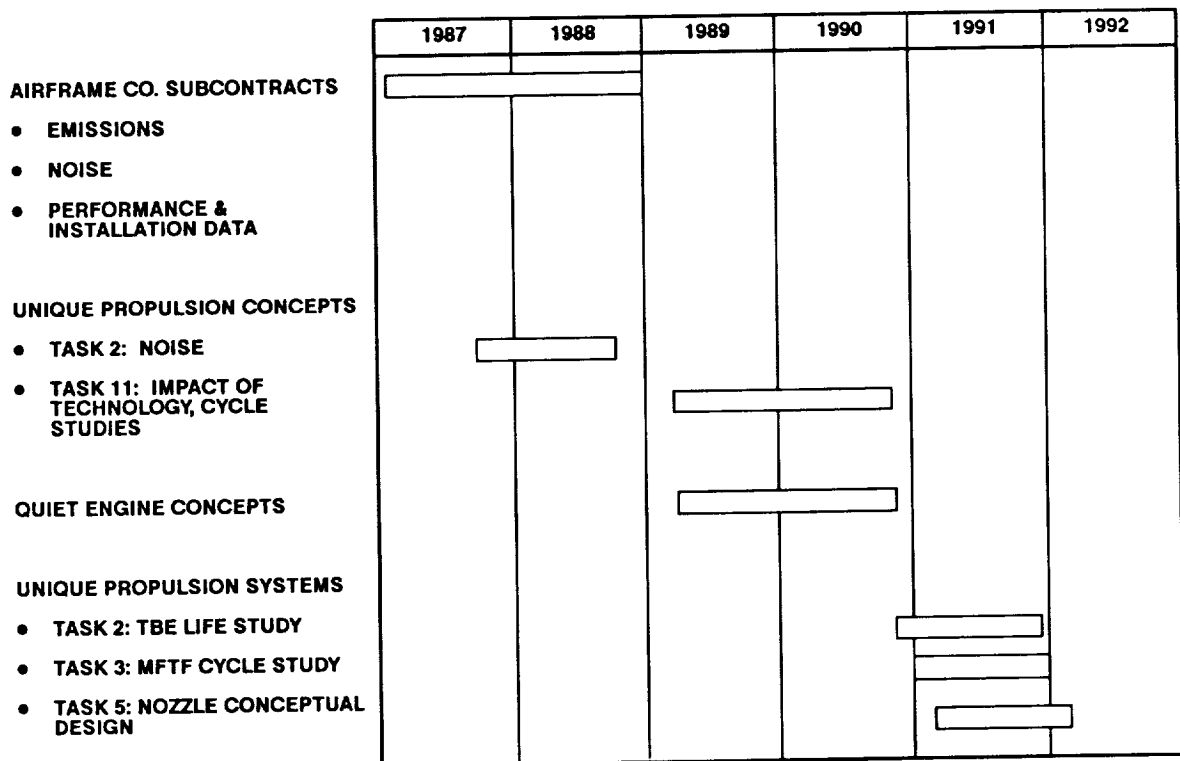


Figure 1

P&W ENGINE CONCEPTS

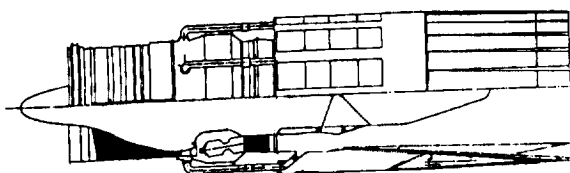
Shown in Figure 2 are four engine concepts which have been , or are being, investigated for potential future application to a High Speed Civil Transport. The turbine bypass engine (TBE) is a single spool turbojet with an oversized compressor and a compressor bleed system that bypasses flow around the turbine. This feature enables the TBE to operate at maximum turbine inlet temperature over the entire flight envelope. It also provides higher compressor pressure ratio and more thrust variation at constant airflow than a comparable turbojet during part throttle operation. It has an inherently high exhaust jet velocity and must rely on a very effective suppressor nozzle to achieve the FAR 36 Stage III noise goal.

The turbine bypass engine equipped with an inlet flow valve is intended to provide lower exhaust jet velocity through increased inlet total airflow at takeoff, while maintaining the turbojet cycle for climb and supersonic cruise operation.

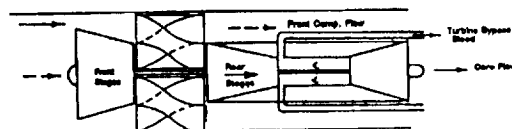
The variable stream control engine (VSCE) is a moderate bypass ratio twin spool turbofan which uses fan duct augmentation for takeoff, transonic/supersonic acceleration and supersonic cruise. The VSCE derives its name from the ability to independently control the primary and fan duct exhaust streams via its two burners and two exhaust throat areas.

The mixed flow turbofan (MFTF) is the type of engine being widely used for many current and planned military aircraft. It is typically a low bypass ratio twin spool configuration and may be equipped with an afterburner for thrust augmentation. For the HSCT application, the use of an afterburner is being considered for use at thrust critical transient conditions, such as transonic acceleration, but may not be necessary. The MFTF has an inherently lower exhaust jet velocity than the TBE and would not require as much noise suppression in the nozzle to meet the FAR36 Stage III goal.

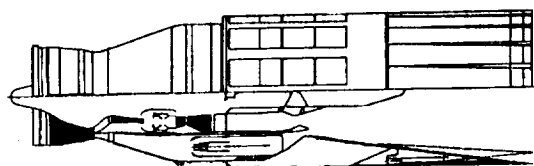
TURBINE BYPASS ENGINE



TURBINE BYPASS ENGINE WITH INLET FLOW VALVE



VARIABLE STREAM CONTROL ENGINE



MIXED FLOW TURBOFAN

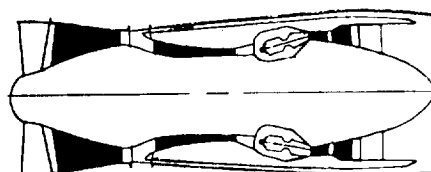


Figure 2

P&W COMBUSTOR FOCUS

RICH BURN-QUICK QUENCH CONCEPT

Pratt & Whitney is focusing its High Speed Research (HSR) combustor technology development on the rich burn quick quench (RBQQ) concept, which is illustrated in Figure 3, to achieve very low levels of oxides of nitrogen (NO_x) emissions. Combustion takes place in three distinct zones: the fuel rich zone, rapid quench zone and fuel-lean zones.

All of the fuel is injected and reacted in the fuel rich zone. Because of the lack of enough oxygen for complete combustion, the rate of formation of NO_x is low. To complete the combustion process, which consists of carbon monoxide to carbon dioxide conversion and smoke oxidation, the rich zone combustion products pass through a second reaction zone in which the mixture strength is lean and temperature sufficiently high to carry out the reactions, but avoiding the higher levels at which formation of NO_x can be accelerated. The rich-to-lean mixture transition must be accomplished in the quick quench section of the combustor located between the rich and lean zones. Large quantities of air are introduced in this section to mix rapidly without accumulating time at elevated temperatures.

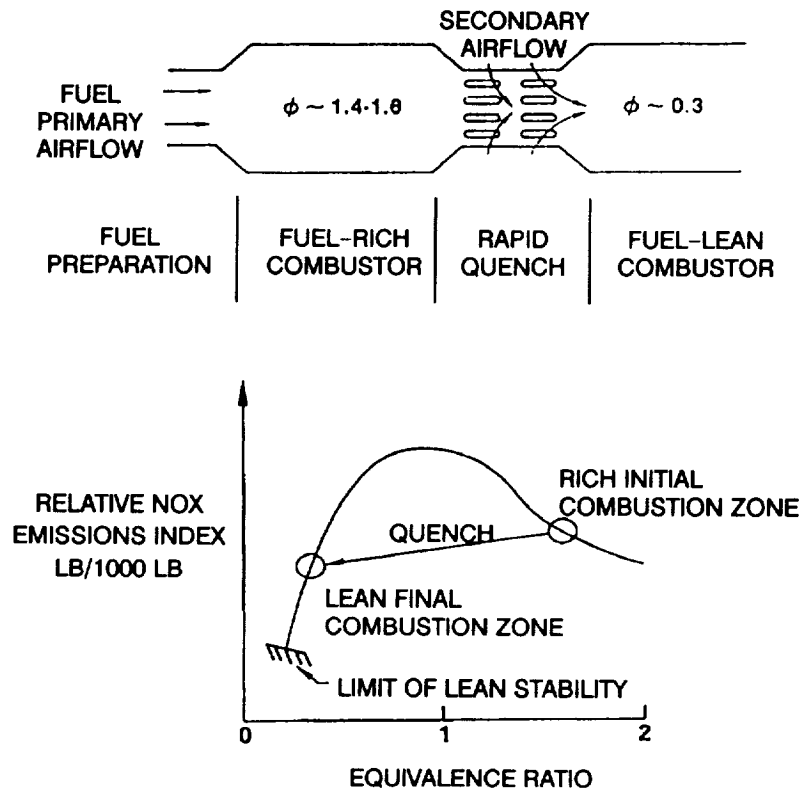


Figure 3

MIXER EJECTOR NOZZLE CONCEPT

LARGE FLOW ENTRAINMENT REDUCES JET NOISE

The mixer/ejector suppressor nozzle concept illustrated in Figure 4 is currently being investigated under the HSR low noise nozzle technology development program. The nozzle concept relies on a large amount of ambient airflow entrainment to rapidly mix with the high temperature exhaust flow, thereby lowering the jet velocity and the associated jet noise. It has a retractable mixer which is deployed at takeoff and stowed for cruise.

Also shown in Figure 4 is the theoretical reduction in noise as a function of the amount of entrained flow. The Pratt & Whitney goal is to achieve over 100% flow entrainment and approximately 20 db noise reduction in the nozzle.

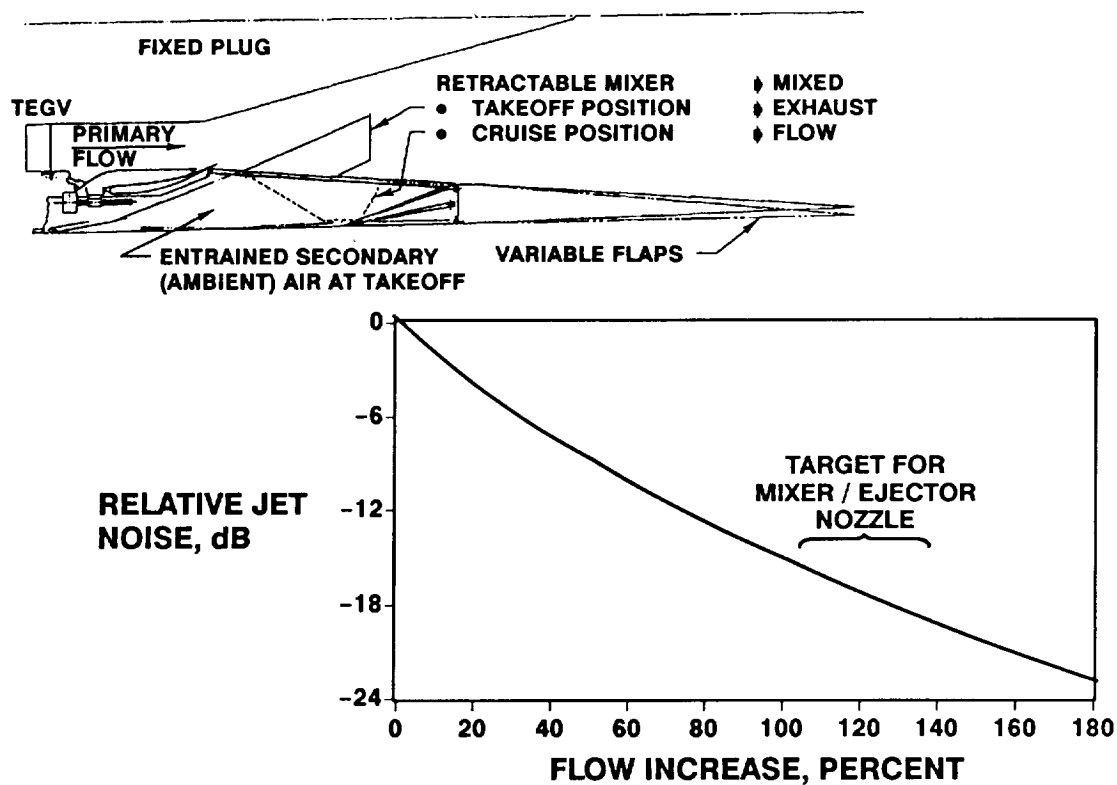


Figure 4

TECHNOLOGY IMPACT ON NO_x EMISSIONS
MATURE RBQQ COMBUSTOR REDUCES NO_x UP TO 85%

The projected impact of propulsion technology advances on NO_x emissions, takeoff noise and integrated propulsion/airframe system performance will now be described. Figure 5 presents the supersonic cruise NO_x emissions trend for three technology time period TBE's from current technology with entry into service (EIS) in 1995 to year 2005 EIS. If current technology combustors were utilized, NO_x would more than double for the year 2005 EIS engine due to its 200°F increase in combustor inlet and exit temperatures and over 50% increase in combustor pressure level. The mature RBQQ combustor is projected to reduce NO_x emissions up to 85% for this engine or 70% relative to the current technology cycle and combustor.

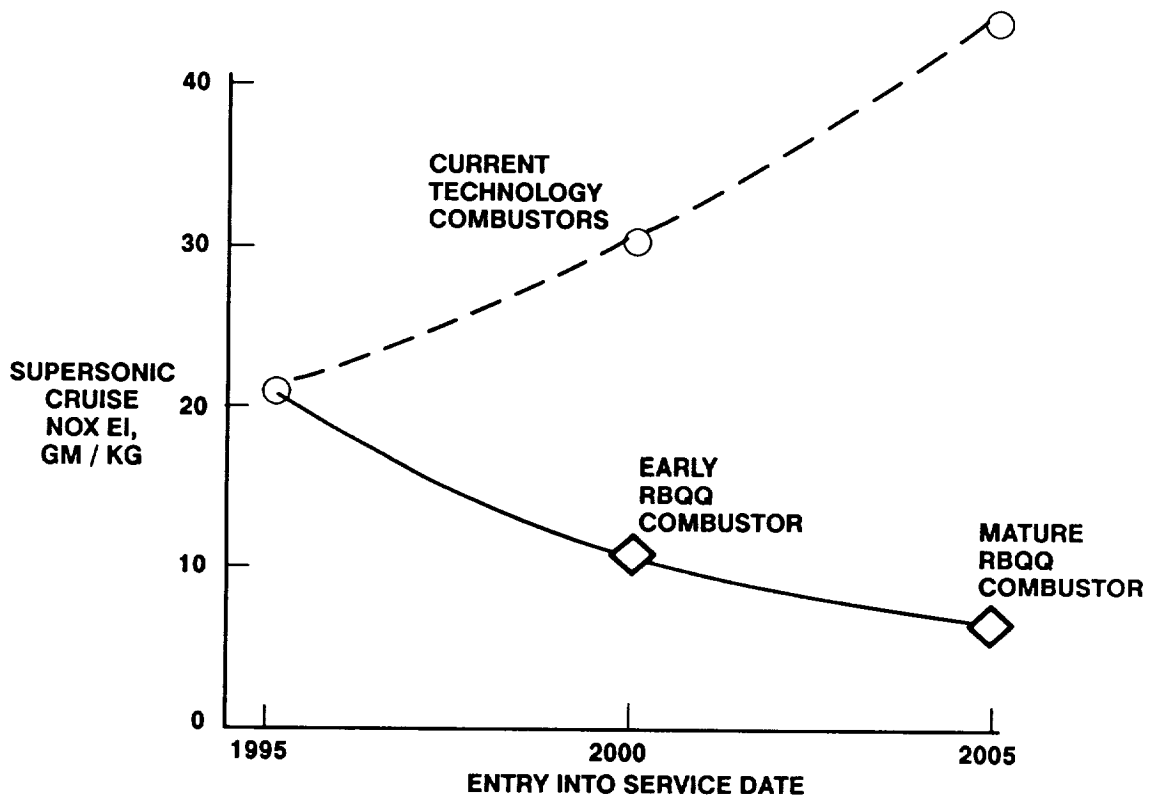


Figure 5

TECHNOLOGY IMPACT ON SIDELINE NOISE CHARACTERISTICS

MACH 2.4 TURBINE BYPASS ENGINES – 600 LB/SEC AIRFLOW SIZE

The jet noise comparison for the same 1995, 2000 and 2005 EIS TBE's is presented in Figure 6. The unsuppressed jet noise increases with increased thrust (and attendant jet velocity) for the later time period engines due to the higher combustor temperatures. For the 1995 EIS engine a conventional tube/chute mechanical noise suppressor is estimated to provide about 12 db noise reduction, but is still 8 db above the FAR36 Stage III rule. The mixer/ejector suppressor nozzle concept utilized for the later time frame engines is projected to provide on the order of 20 db suppression (based on 120% flow entrainment), but still is 2 to 3 db above Stage III at maximum power. However, the noise goal can be met throttling the engines while still providing more thrust than the 1995 EIS engine.

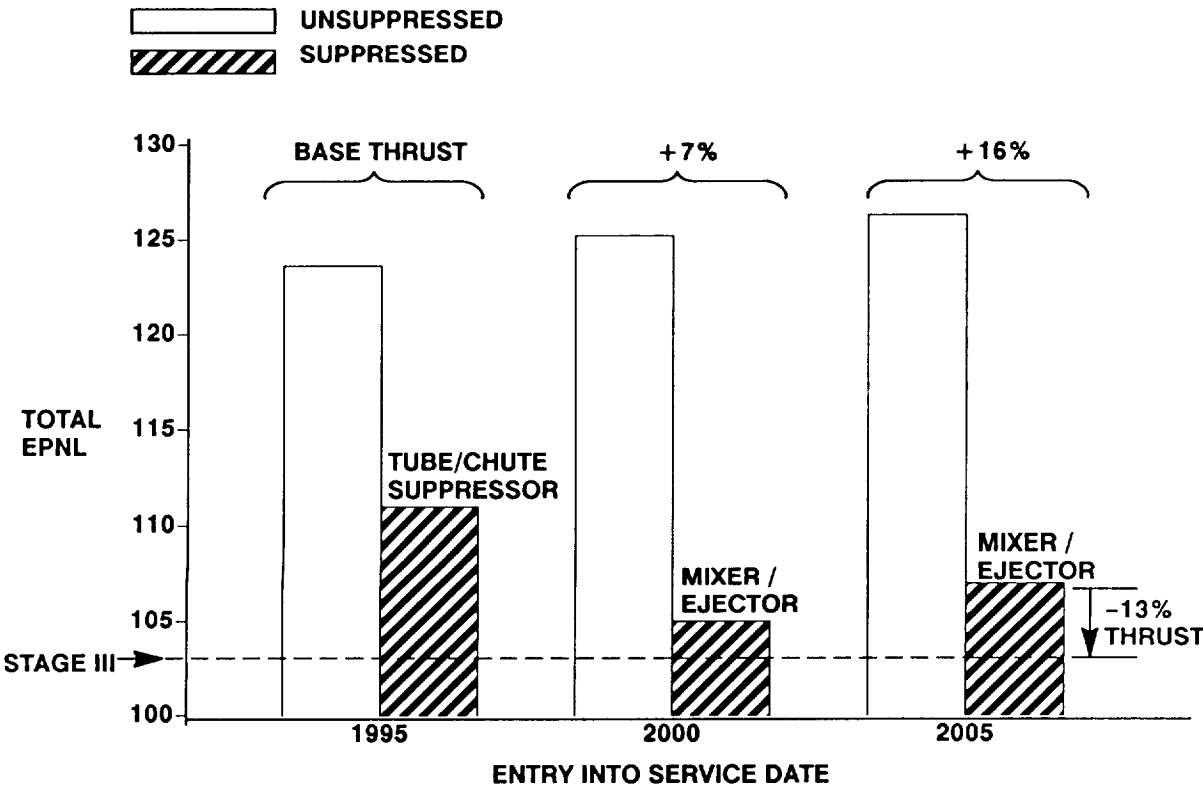


Figure 6

TECHNOLOGY IMPACT ON TAKEOFF GROSS WEIGHT **PROVIDES UP TO 12% TOGW REDUCTION**

The results of the integrated propulsion/airframe system evaluation of the 1995, 2000 and 2005 EIS Mach 2.4 TBE's are illustrated in Figure 7. The figure shows aircraft takeoff gross weight (TOGW) required for 5000 nm design range as a function of engine corrected airflow (WAT2) divided by TOGW. Noted on each of the curves are the WAT2/TOGW values needed to satisfy the various engine sizing constraints. The solid symbols on the year 2000 and 2005 curves represent the points sized for the required takeoff field length while meeting the Stage III sideline noise goal. The 1995 and 2000 TBE critical engine sizes are set by the time to climb criteria. The 1995 TBE produces a sideline noise level of 110 db at the time-to-climb sized point as noted on the curve. A point is also noted on the 1995 TBE curve that reduces the noise by just one db via throttling back and oversizing the engine at takeoff, and is obviously an unacceptable penalty to pay for noise reduction. The time to climb sizing criteria for the year 2000 engine provides a larger engine than required to meet the noise goal. The year 2005 TBE engine size is set almost simultaneously by the time-to-climb and takeoff field length/Stage III noise criteria. The payoff for the year 2005 engine relative to the current technology year 1995 engine is a 12% takeoff gross weight reduction and 7 1/2 EPNdb reduction is sideline noise.

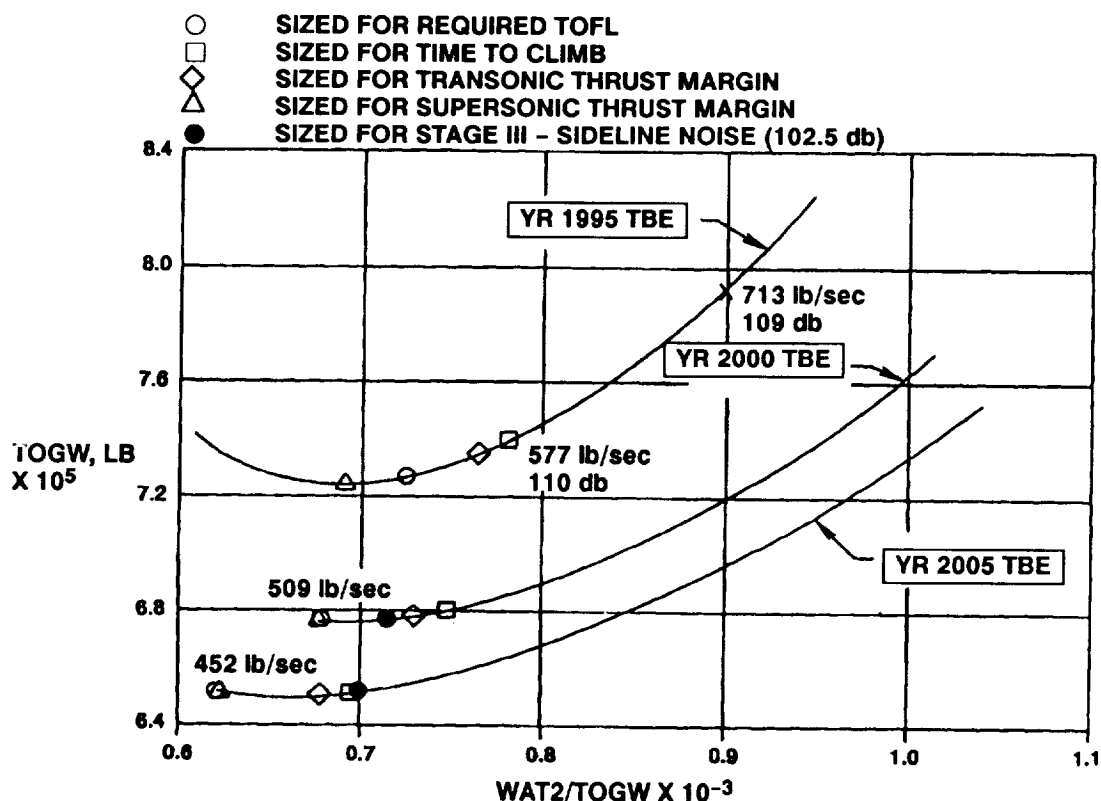


Figure 7

MACH 2.4 TBE VERSUS VSCE FLYOFFS **TBE PROVIDES 12% TOGW OR 19% RANGE IMPROVEMENT**

Shown in Figure 8 is a comparison between the year 2005 EIS TBE and VSCE designed for Mach 2.4 cruise. The comparison is shown both on the basis of takeoff gross weight for a design range of 5000 nm and range for a fixed TOGW. The figure shows a 12% TOGW or 19% range advantage for the TBE. The contributions to the TBE's range advantage are depicted and are shown to be due primarily to improved fuel consumption during climb and cruise. These results are for an all-supersonic mission profile. A mixed subsonic/supersonic mission with a 1000 nm subsonic cruise leg was also considered. For the mixed mission the TBE range advantage is reduced to about 15% relative to the VSCE. In summary, the system evaluation results show the TBE is clearly superior to the VSCE for a Mach 2.4 cruise application. As will be shown later, studies at Mach 3.2 produced similar results.

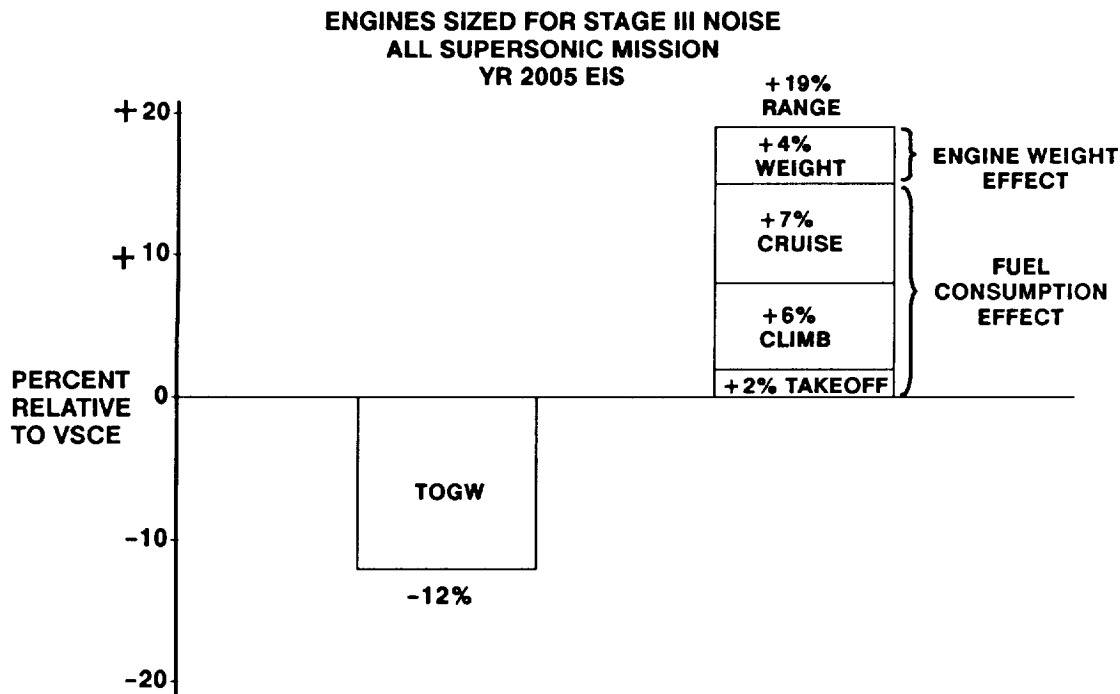


Figure 8

HSCT QUIET ENGINE CONCEPTS (QEC)
MACH 3.2 NOISE REDUCTION CONCEPTS

Two major challenges in the design of propulsion systems for High Speed Civil Transports (HSCT) are complying with noise and emissions environmental standards while providing economically acceptable aircraft. These issues create a dilemma in engine design because low exhaust jet velocities are required to meet takeoff noise regulations while high exhaust jet velocities are required for economical supersonic cruise operation. Previous studies have shown that engines incorporating mechanical suppression concepts to meet FAR Stage III noise regulations must be oversized by 50 to 70% relative to the sizes that will provide the most attractive aircraft economics.

The objective of the Quiet Engine Concept (QEC) study was to examine propulsion concepts that can achieve a large increase in airflow during takeoff operation to reduce the average exhaust velocity to acceptable levels. Two methods of accomplishing large flow increases were examined.

The first method utilizes a flow inverter valve between compression system stages to transport flow from the front compression stage around the rear stages while simultaneously ducting additional ambient air into the rear compression stages. This concept can increase engine total airflow by 30 to 70%.

The second method utilizes a mixer/ejector nozzle to increase the engine exhaust flow by up to 120% during takeoff and landing operation.

As shown in Figure 9 these two methods of increasing engine airflow were evaluated for various propulsion concepts to identify their applicability and effectiveness in reducing takeoff noise. Propulsion concepts studied for a Mach 3.2 HSCT included non-augmented turbine bypass engines (TBE), variable stream control engines (VSCE) and non-augmented mixed flow turbofans (MFTF).

- **TURBINE BYPASS ENGINE (TBE) WITH:**
 - **INLET FLOW VALVE AND MIXER EJECTOR NOZZLE**
 - **MIXER EJECTOR NOZZLE**
- **VARIABLE STREAM CONTROL ENGINE (VSCE) WITH:**
 - **INLET FLOW VALVE AND MIXER EJECTOR NOZZLE**
 - **MIXER EJECTOR NOZZLE**
- **NON AUGMENTED MIXED FLOW TURBOFAN WITH:**
 - **MIXER EJECTOR NOZZLE**

Figure 9

TBE INLET VALVE/EJECTOR NOZZLE CONCEPT SCHEMATIC

In this concept, illustrated in Figure 10, the 120% exhaust flow increase is achieved through the use of an inlet flow valve and an ejector nozzle. The inlet valve is positioned between the first and second stage of the compressor, and is used during takeoff to divert the front stage exhaust flow around the rear stages and bring in 500 lb/sec ambient air to supply the rear stages. During climb/acceleration and cruise operation, the inlet valve is repositioned so that all the flow entering the front stage passes through the rear stages and the auxiliary inlet air doors are closed.

The ejector nozzle is used to entrain 281 lb/sec flow during takeoff to increase the total exhaust flow to 1450 lb/sec. and reduce the jet velocity to the required 1450 ft/sec. A mixer is used to achieve a flat velocity profile exiting the nozzle.

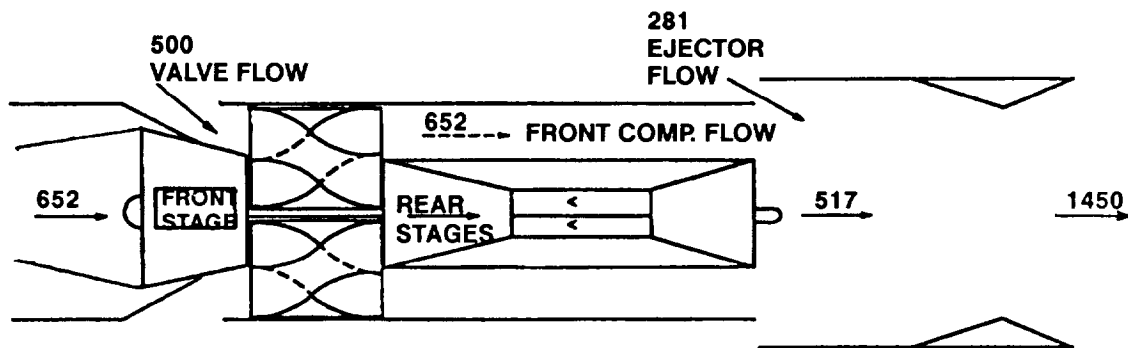


Figure 10

IMPACT OF INLET FLOW VALVE **ENGINE LENGTH INCREASED BY 60 INCHES**

As shown in Figure 11, incorporation of the inlet flow valve into the flowpath requires significant flowpath changes to the high pressure compressor. When a valve is incorporated into the engine, the corrected airflow entering the rear stages will vary significantly between high mode and low mode operation. To insure that the rear stages would be compatible with the specific flow variations, the area at the rotor inlet was increased relative to the conventional engine. At the sea level takeoff design point the specific flow into rear aft stages during high mode operation is 40.6 compared to 36.1 during low mode operation. Analysis indicated that this range of specific flows produced good efficiency during both high and low mode operation.

An additional item of concern is the pressure distortion which will occur when the valve transitions from high to low mode operation. The front and rear stages of the compressor must be designed with sufficient stall margin to allow stable transient operation. Accordingly, the compressor rear flowpath was modified from a Constant Mean Diameter (CMD) to a Constant Outer Diameter (COD) configuration and the entire flowpath was moved radially outward. This process increased the average mean wheel speed through each airfoil row, improving the stage work capability at the expense of additional weight. Since the inverter valve was designed to accept axial inlet and deliver axial exit flow, vanes incorporating variable trailing edge flaps were positioned at the inlet and exit of the inverter valve. The vane geometry is set as required to achieve compatibility with the change in flow ratios between high and low mode operation.

Incorporation of an inlet flow inverter valve in the TBE increases the engine length by 60 inches and the weight by 2740 lb or 22%. The inlet valve weighs 1280 lb, and the modifications to the basic engine weight 1460 lb.

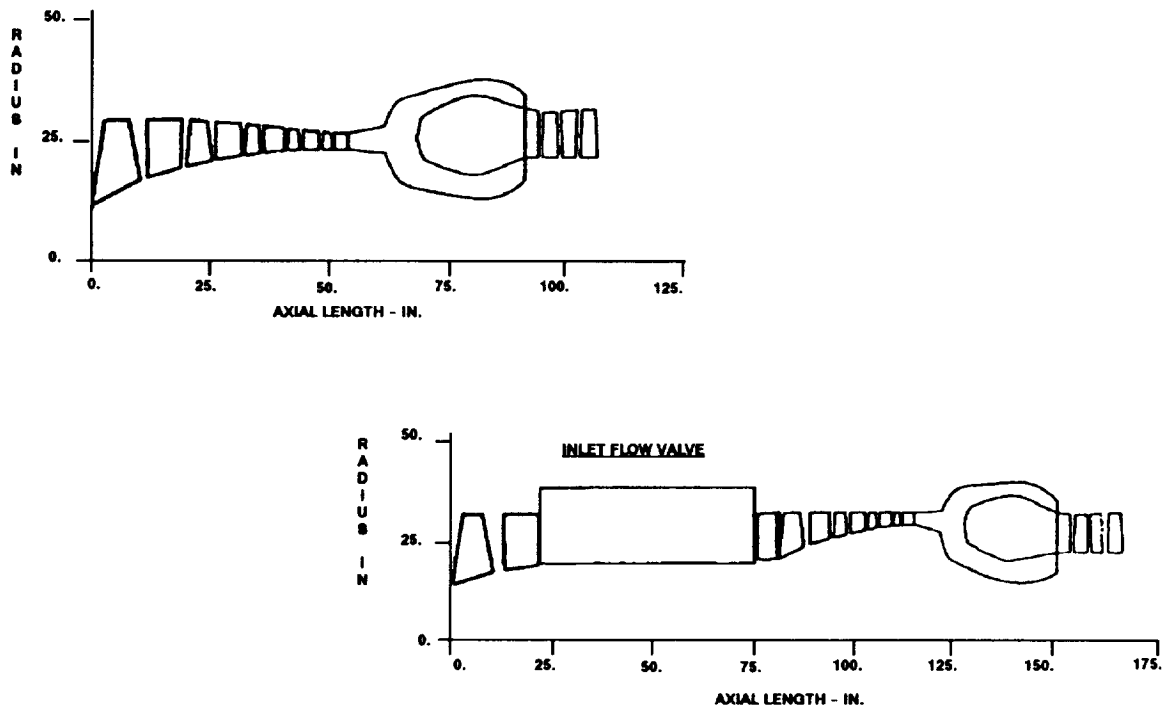


Figure 11

MACH 3.2 QUIET ENGINE CONCEPTS

IMPACT OF NOISE REDUCTION CONCEPTS ON TBE POWERED MACH 3.2 HSCT

Mission analyses were conducted for a TBE powered Mach 3.2 HSCT which carries a passenger load of 61,500 lb for a distance of 5000 n. mi. In order to achieve a takeoff field length (TOFL) of 12,000 feet, a total net thrust (FNTOT) to takeoff gross weight (TOGW) ratio of 0.287 is required.

In the 1970s, engines with mechanical noise suppressors (MNS) and acoustically treated nozzles were examined. Figure 12, Column 1 shows that such an engine, sized for the TOFL requirement, achieves a sideline jet noise level of 111, which is 9 EPNdB above the Stage 3 requirement of 102 EPNdB for a 675,000 lb TOGW aircraft.

If a mixer/ejector nozzle (MEN) can entrain 770 lb/sec flow and mix it fully with the 660 lb/sec exhaust flow of the TBE to achieve an effective exhaust velocity of 1450 ft/sec, column 2 shows that the FAR Stage 3 noise requirement can be met with a 687,000 lb TOGW aircraft.

Column 3 shows that if an inlet flow valve (IFV) with 74% flow and a mixer ejector nozzle (MEN) with 43% flow entrainment are used, the aircraft TOGW increases to 768,000 lb because the inlet flow valve increases the propulsion system weight by 22%.

	<u>MNS</u> <u>NOZZLE</u>	<u>M/E</u> <u>NOZZLE</u>	<u>IFV +</u> <u>M/E NOZZLE</u>
TOGW, LB	674,800	686,700	767,800
ENGINE FLOW SIZE, LB/SEC	630	641	717
ENGINE WEIGHT, LB	11490	12220	16675
SIDELINE EXHAUST FLOW, LB/SEC	650	1430	1600
• MAIN INLET + FUEL	650	660	740
• INLET VALVE	---	---	550
• EJECTOR NOZZLE	---	770	310
SIDELINE EXHAUST VELOCITY, FT/SEC	2760	1450	1450
UNSUPPRESSED NOISE, EBNdB	123	101	102
SUPPRESSED NOISE, EPNdB	111	---	---
STAGE III RULE, EPNdb	102	102	102.5

Figure 12

MACH 3.2 QUIET ENGINE CONCEPTS

IMPACT OF NOISE REDUCTION CONCEPTS ON VSCE POWERED MACH 3.2 HSCT

In the 1970's variable stream control engines with mechanical noise suppressors (MNS) were examined. During takeoff operation, the duct burner is on and produces a duct stream exhaust velocity that is 70% higher than that of the core stream. The Inverted Velocity Profile (IVP) produces an unsuppressed jet velocity of 119 EPNdB. Mechanical noise suppressors for this concept provide an additional 2 EPNdB reduction in noise, as shown in Figure 13, Column 1. If the engines are sized to achieve the 12,000 ft. takeoff field length, a sideline jet noise of 117 EPNdB is produced.

In order to achieve the Stage 3 noise regulation, a mixer/ejector nozzle (MEN) with 120% flow entrainment is required. Column 2 shows that a VSCE with a MEN produces an aircraft TOGW of 800,000 lb.

	BASELINE <u>IVP, MNS</u>	MIXER EJECTOR <u>NOZZLE</u>
TOGW, LB	744,300	799,800
ENGINE FLOW SIZE, LB/SEC	682	733
ENGINE WEIGHT, LB	11710	14110
SIDELINE EXHAUST FLOW, LB/SEC	705	1635
• MAIN INLET + FUEL	705	755
• EJECTOR NOZZLE	---	880
SIDELINE EXHAUST VELOCITY, FT/SEC	2730	1450
UNSUPPRESSED NOISE, EBNdB	119	103
SUPPRESSED NOISE, EPNdB	117	---
STAGE III RULE, EPNdB	102	103

Figure 13

MACH 3.2 QUIET ENGINE CONCEPTS

TBE AND MFTF PROVIDE TOGW REDUCTION OF 14 TO 16% OVER VSCE

Mixer/ejector nozzles have been evaluated for a non-augmented turbine bypass engine (TBE), a non-augmented mixed turbofan (MFTF) and duct burning variable stream control engine (VSCE). The results are summarized in Figure 14. The TBE concept provides the best supersonic cruise fuel consumption, while the MFTF provides the lightest weight propulsion system. The VSCE, which operates with the duct burner on during supersonic cruise, has the highest Mach 3.2 cruise TSFC and requires the largest aircraft to satisfy the mission. The TBE and MFTF powered aircraft are 14 and 16% lighter than the VSCE powered aircraft, respectively.

	<u>VSCE/MEN</u>	<u>TBE/MEN</u>	<u>MFTF/MEN</u>
TAKEOFF GROSS WEIGHT, LB	799,800	686,700	675,300
ΔTOGW, %	BASE	-14	-16
ENGINE FLOW SIZE, LB/SEC	733	641	631
ENGINE WEIGHT, LB	14,110	12,220	10,960
MACH 3.2 CRUISE TSFC, LB/HR/LB	1.72	1.63	1.65
SIDELINE NOISE, EPNdB	103	101	101
STAGE III RULE, EPNdB	103	102	102

Figure 14

TURBINE BYPASS ENGINE LIFE STUDY

OBJECTIVES

A wide variety of propulsion system concepts have been considered for application in a 2nd generation supersonic transport. Based upon these studies, the Turbine Bypass Engine (TBE) has emerged as one of the promising candidates. Selection of the best propulsion system requires more in-depth studies to identify the optimum cycle and configuration for each engine. The objectives of the Turbine Bypass Engine Life Study are: (1) to update the conceptual definition of a Mach 2.4 TBE to include commercial life requirements and the latest material and structural technology projections and (2) to define critical component technology programs which must be carried out prior to initiation of engine full-scale development. (See Figure 15). The engine incorporates aerodynamic, material, and structural technologies projected to have technical readiness in the year 2000, with a corresponding Entry Into Service in 2005.

- **UPDATE THE CONCEPTUAL DESIGN DEFINITION OF MACH 2.4 TBE TO INCLUDE COMMERCIAL LIFE REQUIREMENTS FOR A YEAR 2005 ENTRY INTO SERVICE DATE**
- **DEFINE CRITICAL COMPONENT TECHNOLOGY PROGRAMS WHICH MUST BE CARRIED OUT PRIOR TO INITIATION OF FULL SCALE DEVELOPMENT**

Figure 15

HIGH SPEED CIVIL TRANSPORT ENGINES

SUPERSONIC CRUISE MISSION REQUIRES MAXIMUM TEMPERATURE OPERATION FOR MUCH HIGHER PERCENTAGE OF TIME

Achieving commercial life in an HSCT propulsion system poses a substantial challenge to the engine designer. An HSCT engine operates at near maximum cycle temperatures and rotational speeds from transonic acceleration through the end of supersonic cruise, resulting in the majority of the mission spent at the most severe combination of stress levels and temperature conditions. In contrast, current subsonic transports operate at the most severe engine conditions only during takeoff, generally less than 1% of the total flight time. A comparison of typical turbine temperature histories for a future HSCT versus a current subsonic transport is shown in Figure 16.

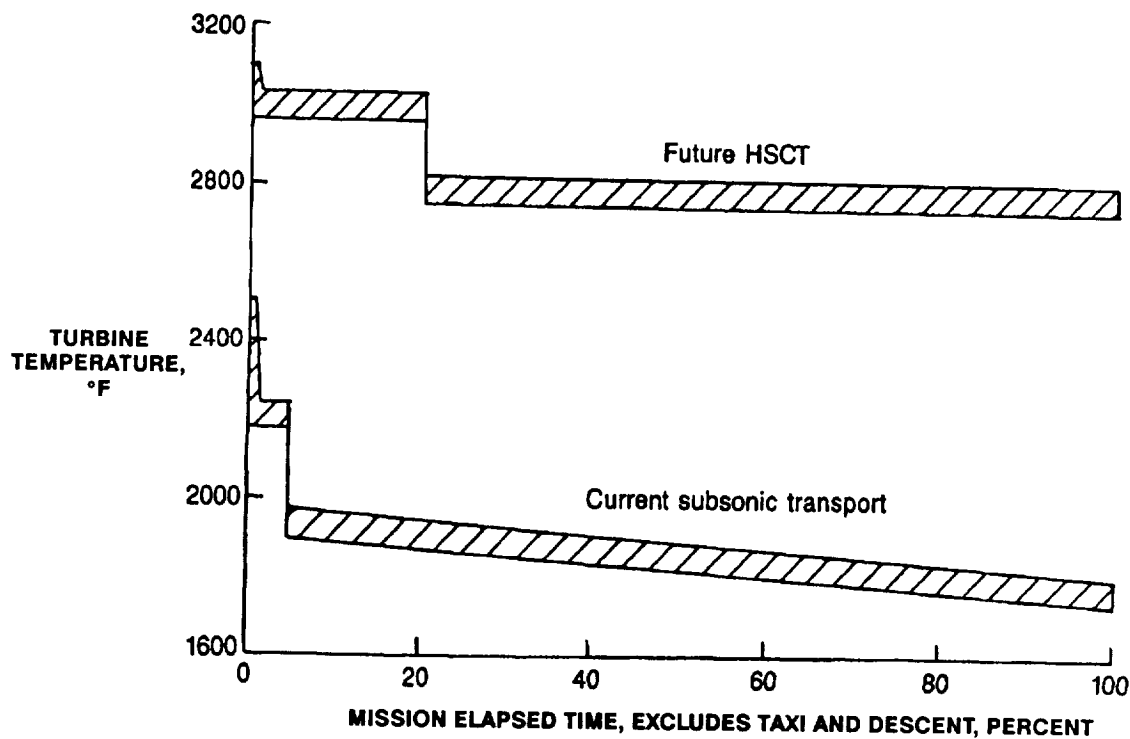


Figure 16

TURBINE BYPASS ENGINE LIFE STUDY **CYCLE & CONFIGURATION GROUND RULES**

The primary TBE cycle parameters for the life study were defined to be consistent with the groundrules established by the P&W/GEAE HSCT Propulsion Team. These groundrules, shown in Figure 17, resulted from previous studies conducted under HSR Phase I coupled with updated estimates of projected material capabilities, structural concepts and cooling technologies. The maximum compressor discharge temperature was limited by material constraints in the aft compressor stage airfoil and disk rim. Additional constraints on the compressor discharge temperature were cooling requirements for the low NO_x combustor liner and the turbine blade attachments. The maximum combustor exit temperature was limited based upon achieving acceptable turbine airfoil cooling with the specified compressor discharge temperature. Although these temperatures may not seem aggressive when compared to military engines, consideration of the HSCT duty cycle makes them highly aggressive.

The primary parameter varied in the flowpath study is turbine maximum AN², which establishes the rotational speed of the engine. High AN² designs have heavier, more complicated disks and attachments but may achieve weight and drag reductions by reducing the number of airfoils, reducing the engine diameter, and/or reducing the engine length. However, at some level, engine life will be reduced or the weight/performance benefits will be offset by other considerations. For each configuration, iterations are performed between the performance and flowpath to account for any required changes in secondary flows and/or component efficiencies. Selected compressor and turbine attachments and disks are then designed to insure structural feasibility and aid in establishing engine weight trends. A mission analysis is then performed for each engine to identify the optimum set of component aero/mechanical design groundrules.

CYCLE	INLET CORRECTED AIRFLOW SIZE, LB/SEC	650
	PRESSURE RATIO	19
	T41 HOT DAY TAKEOFF, °F	2900
	T41 STD DAY MACH 2.4 CLIMB, °F	2800
	T3 MAX, °F	1250
	TAKEOFF THRUST, LB	58000
TURBINE AN² (SETS RPM), IN² – RPM²		400 – 500 X 10⁸

Figure 17

TURBINE BYPASS ENGINE LIFE STUDY

DUTY CYCLE - ALL SUPERSONIC AND AVERAGE MISSIONS

The HSCT will be sized for an all-supersonic mission with an assumed design range of 5000 nautical miles. However, a typical mission will result in a mixture of subsonic/supersonic flight with an average range on the order of 3500 nautical miles. The TBE engine will be designed to meet commercial life requirements based upon the typical flight profile. Lower life will result from utilization in an all-supersonic mission environment. The TBE life study will determine the difference in engine life between an all supersonic and a typical mixed mission.

Figure 18 depicts the variation in rotor speed, compressor exit temperature and turbine inlet temperature as a function of time for the all-supersonic and mixed missions. Note the large reduction in all three parameters for subsonic cruise operation. This serves to further illustrate the severity of supersonic cruise operation relative to subsonic.

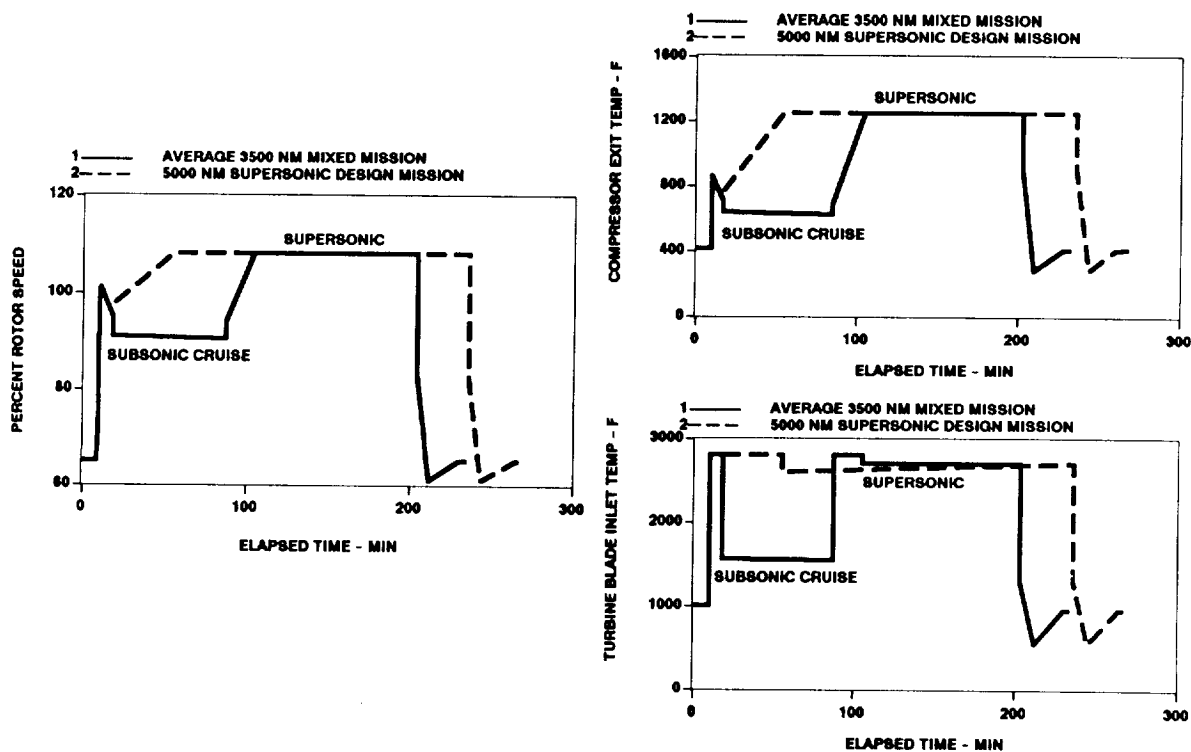


Figure 18

TURBINE BYPASS ENGINE LIFE STUDY

FLOWPATH COMPARISON

Some parametric flowpaths considered during this study are shown in the Figure 19, compared against the baseline engine configured with a turbine maximum $AN^2 = 450 \times 10^8 \text{ in}^2\text{-rpm}^2$. The compressor and turbine configurations for each engine were optimized to achieve the best combination of airfoil count, flowpath shape, and flowpath elevation to achieve efficiency and stall margin goals. All of the compression systems feature advanced low aspect ratio 3-D swept aerodynamics to reduce shock losses. The stators feature a "hyperbow" design to control endwall boundary layers, reducing secondary flow losses and improving stability. The combustor is representative of the low NO_x Rich-Burn Quick-Quench concept. The turbine features advanced 3-D aerodynamics for improved efficiency.

Going from maximum $AN^2 = 400$ to $450 \times 10^8 \text{ in}^2\text{-rpm}^2$ results in lower compressor and turbine elevations due to increased rpm capability and shorter length. Progressing from 450 to $500 \times 10^8 \text{ in}^2\text{-rpm}^2$ still provides a reduction in compressor and turbine elevations, but a 2 inch length increase. A 6 stage compressor flowpath has also been defined which reduces engine length about 10 inches, but results in compressor evaluations comparable to the maximum $AN^2 = 400 \times 10^8 \text{ in}^2\text{-rpm}^2$ case.

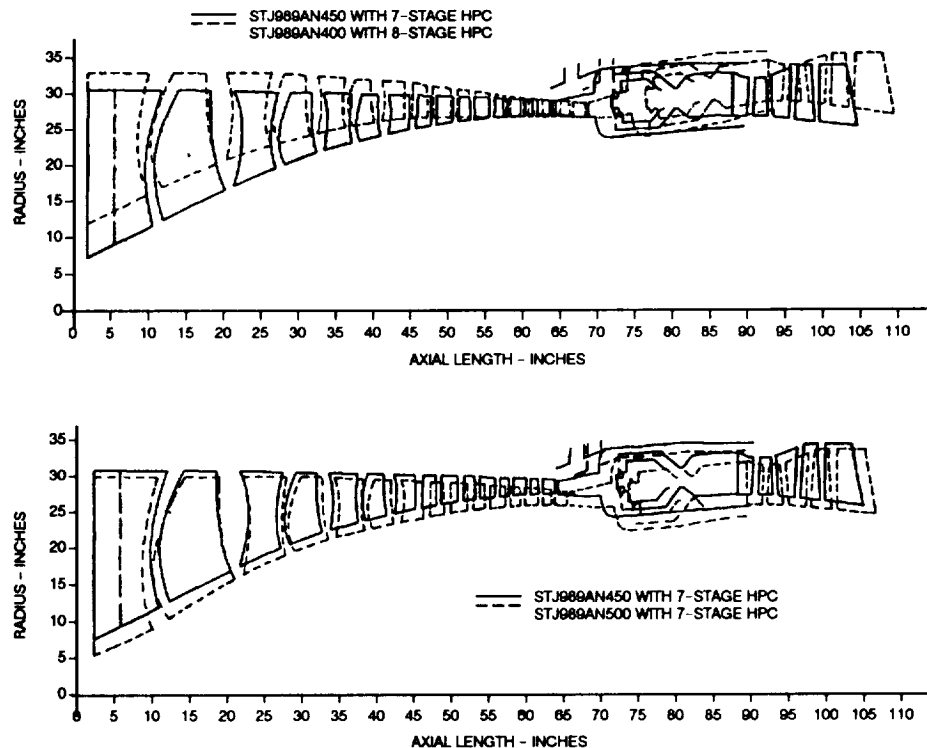


Figure 19

MIXED FLOW TURBOFAN STUDY

OBJECTIVES

The objectives of the mixed flow turbofan study are shown in Figure 20. This study will investigate the potential of low bypass ratio, mixed exhaust cycles and configurations, including augmented and non-augmented systems, for a Mach 2.4 application.

Economically attractive candidates from the cycle matrix will be carried through flowpath and mechanical design evaluation to provide weight, price, and maintenance cost estimates. Resulting engines will be “flown” on a reference aircraft model to establish relative merits on the basis of integrated propulsion/airframe system performance and economics. Performance and installation characteristics for the most promising engine will be provided to NASA and two airframe contractors in the form of data packs. Updates to the technology plan will be made based on any new requirements arising from this task.

- **CONDUCT EVALUATION OF MACH 2.4 MFTF CYCLES**
- **SELECT CYCLE(S) FOR CONCEPTUAL DEFINITION TO INCLUDE COMMERCIAL LIFE REQUIREMENTS FOR A YEAR 2005 ENTRY INTO SERVICE DATE**
- **DEFINE THE CRITICAL COMPONENT TECHNOLOGY PROGRAMS WHICH MUST BE CARRIED OUT PRIOR TO INITIATION OF FULL SCALE DEVELOPMENT**

Figure 20

MIXED FLOW TURBOFAN STUDY
CYCLE MATRIX (20 CYCLE COMBINATIONS)

The cycle matrix shown in Figure 21 covered fan pressure ratios (FPR) from 3.8 (maximum for a two stage fan) up to 5.0 for a three stage fan. Each cycle was defined with a maximum turbine blade inlet temperature (T41) of 2900°F and a cycle overall pressure ratio (OPR) at sea level takeoff determined by a maximum compressor exit temperature of 1250°F. Varying the sea level takeoff turbine temperature while holding climb maximum T41 fixed introduced variations in “throttle ratio”, which determined sea level reference bypass ratio (BPR) as well as BPR excursion from sea level to top of climb. The takeoff T41 – FPR combinations resulted in exhaust velocities from 2100 to 2800 feet per second. This matrix offers trades in subsonic and supersonic thrust specific fuel consumption versus thrust capability (engine sizing).

FAN PRESSURE RATIO	3.8 TO 5.0
THROTTLE RATIO (T41 CLIMB / T41 SLS)	1.05 TO 1.25
MAX COMPRESSOR EXIT TEMP, °F	1250
MAX TURBINE BLADE INLET TEMP, °F	2900
BYPASS RATIO	.04 TO .59
TAKEOFF JET VELOCITY, FPS	2113 TO 2818

Figure 21

MIXED FLOW TURBOFAN STUDY **CYCLES COVER WIDE RANGE OF TRANSONIC AND SUPERSONIC THRUST**

Maximum climb thrust (FNT) at both transonic ($M = 1.1$) and supersonic ($M = 2.4$) conditions covers a wide range across the cycle matrix at the base flow size of 650 lb/sec. The trends shown in Figure 22 indicate increasing thrust when lowering design BPR by increasing FPR at constant throttle ratio or when lowering design BPR by increasing throttle ratio (reduced takeoff T41) at constant FPR. The major effect with the latter approach is the steeper supersonic thrust increase relative to transonic, which is a result of the reduced BPR excursion from sea level to altitude by relatively "upmatching" the high spool and higher fan pressure ratio relative to design (flatter operating line).

The 5.0 FPR cycles are limited to low throttle ratios to maintain takeoff T41's sufficient to support a BPR of 0.1 or greater at desirable mixing conditions.

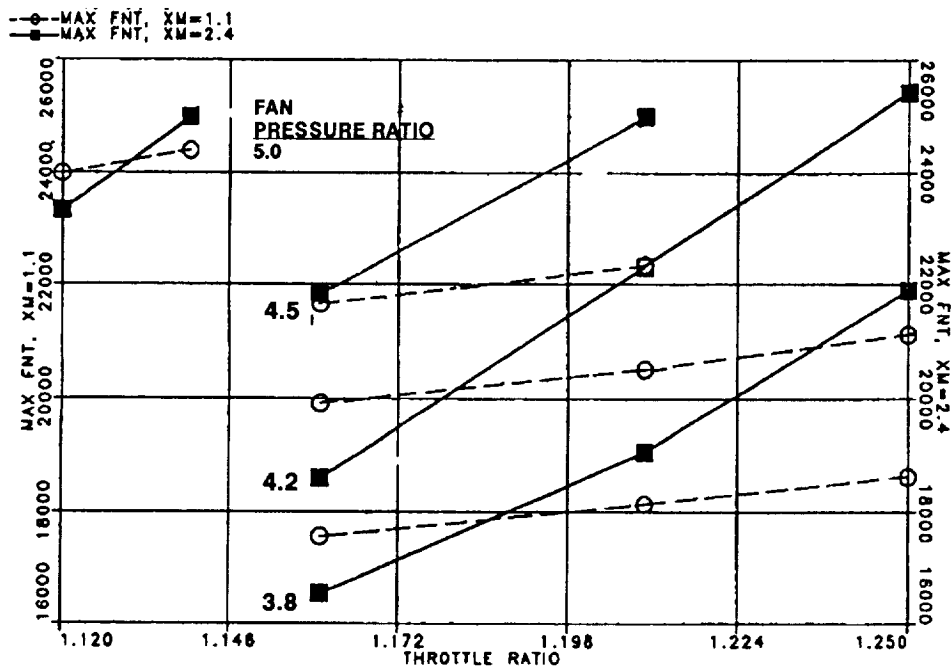


Figure 22

MIXED FLOW TURBOFAN STUDY **REQUIRED ENGINE SIZES (NON AUGMENTED)**

By calculating scaled flow sizes required for each cycle to meet typical airplane thrust requirements at takeoff, transonic climb, and supersonic climb, the critical sizing condition can be determined. All of the cycles shown in Figure 23 are transonic thrust sized. At high throttle ratios, the supersonic sizing criteria approaches the take-off requirement, both of which are well below the transonic sizes; this indicates that a significant engine size reduction could be achieved with the addition of thrust augmentation during transonic climb, which is being considered.

In general, the higher FPR, higher specific thrust cycles result in smaller engine size, approaching the "zero BPR" turbine bypass engine (TBE). However, this size reduction is achieved with higher jet velocity cycles which tend to make achievement of the Stage III noise goal more difficult.

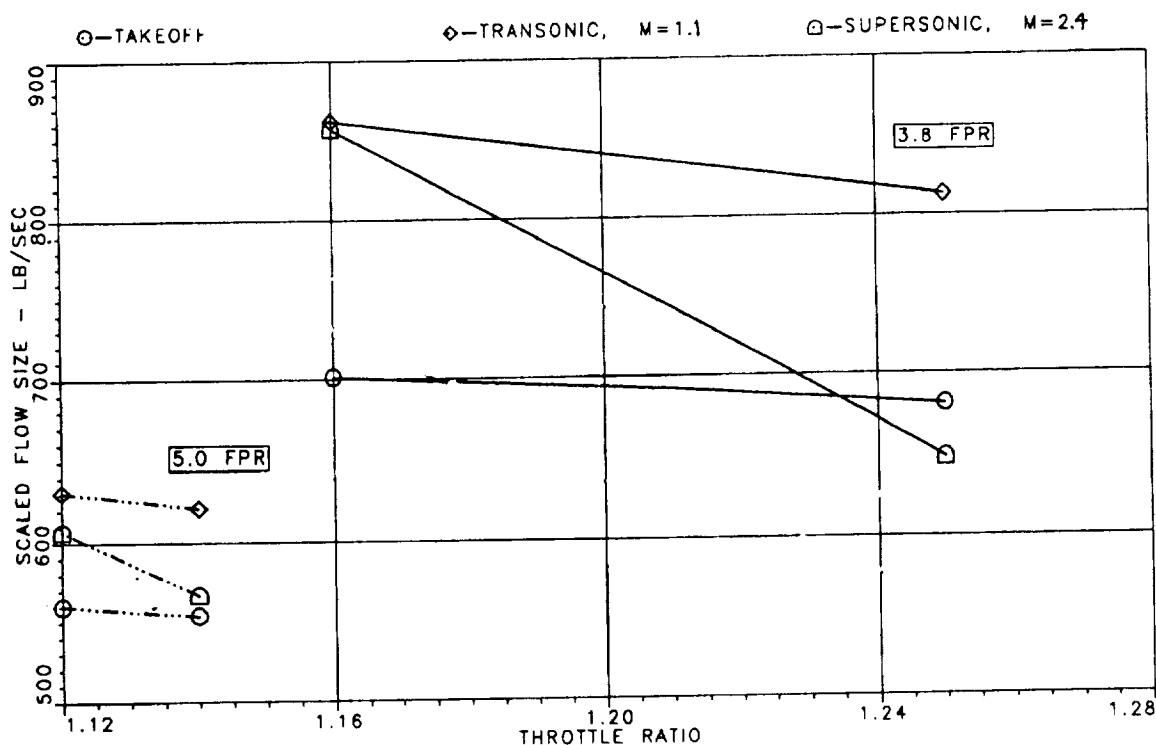


Figure 23

EXHAUST NOZZLE CONCEPTUAL DESIGN

OBJECTIVES

The goal of the nozzle design task is to develop conceptual mechanical designs of both an axisymmetric and a two dimensional mixer ejector nozzle around a Mach 2.4 Turbine Bypass Engine (TBE). The designs will include aerodynamic, acoustic, mechanical, and structural analyses to obtain realistic estimates of dimensions, weight, and performance potential. Critical materials and structural technologies will be identified to achieve a balance between nozzle weight, aerodynamic and acoustic performance, and life. Results will be provided to airframe manufacturers for overall propulsion/airframe system integration and evaluation. (See Figure 24).

- **DEVELOP CONCEPTUAL DESIGNS OF MACH 2.4 AXISYMMETRIC AND TWO DIMENSIONAL (2D) MIXER EJECTOR NOZZLES TO IDENTIFY CRITICAL MATERIALS AND STRUCTURAL TECHNOLOGIES FOR A YEAR 2005 ENTRY INTO SERVICE DATE**
- **COMPARE RESULTING PERFORMANCE, WEIGHT, ACOUSTIC AND DIMENSIONAL CHARACTERISTICS AND PROVIDE TO AIRFRAME MANUFACTURER FOR EVALUATION**

Figure 24

EXHAUST NOZZLE CONCEPTUAL DESIGN

AREA AND OPERATING TEMPERATURE REQUIREMENTS

Operating characteristics for the TBE were evaluated across both a 5000 nm all supersonic mission and a 3500 nm mixed subsonic – supersonic cruise mission. As shown in Figure 25, a wide range of variable throat and nozzle exit areas are required to maintain optimum engine matching and maximum nozzle performance characteristics. The nozzle inlet temperature history during these missions shows extended operation at nearly maximum nozzle temperatures of 1800–1900°F. Other design requirements established include: (1) reverse thrust capability similar to current high BPR turbofans, (2) acoustically treatable nozzle surface area equal to $L/D = 2$, (3) FAR36 Stage III noise rules with 120% ejector flow pumping, and (4) thrust coefficient goals of .982 at cruise and .95 at takeoff, including leakage.

NOZZLE AREA VARIATION REQUIREMENTS – 2005 EIS TBE

A_{THROAT} (A8): 800 – 1180 IN²

TAKEOFF – 855 IN²
SUPERSONIC CRUISE – 1000 IN²

A_{EXIT} (A9): 1400 – 4200 IN²

1400 @ SUBSONIC CRUISE
2120 @ TRANSONIC CRUISE
3940 @ MIXER/EJECTOR DEPLOYED TAKEOFF
4200 @ TOP OF CLIMB

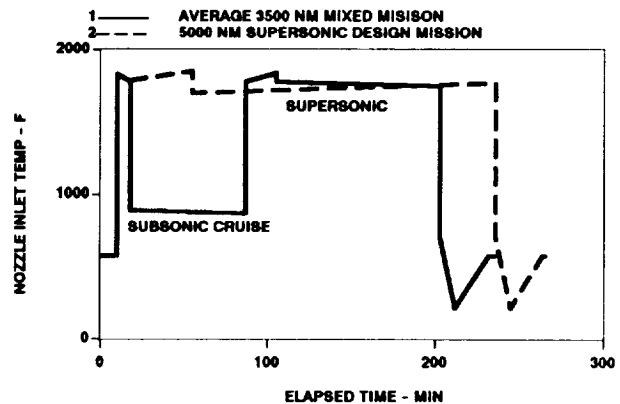


Figure 25

PROPULSION SYSTEMS STUDIES
SUMMARY OF RESULTS / STATUS

A summary of propulsion systems studies results and status is given in Figure 26.

Pratt & Whitney propulsion systems studies during the last several years have quantified the potential payoffs for technology advancements in emissions, noise and overall system performance (as measured by aircraft TOGW or range). The payoffs relative to current technology are 8 db lower airport sideline noise, 85% lower NO_x emissions index and 12% reduction in aircraft TOGW.

Several types of engines have been shown to have the potential to meet the FAR36 Stage III noise goal when equipped with the mixer/ejector nozzle. The VSCE has been shown to be not competitive in terms of TOGW for both Mach 2.4 and 3.2 applications. Therefore, this cycle has not been included in our current study plans.

The TBE and MFTF have been shown to be competitive for Mach 3.2 and therefore, are included in the current Mach 2.4 joint GEAE/P&W study activity.

The mixer/ejector nozzle concept has been identified as the most attractive approach to meeting the FAR36 Stage III noise goal. Consequently, a conceptual design study of axisymmetric and two-dimensional mixer ejector nozzle configurations is underway.

- **PROJECTED TECHNOLOGY ADVANCEMENTS PROVIDE SIGNIFICANT IMPROVEMENTS IN NOISE, EMISSIONS AND AIRCRAFT TOGW**
- **TBE, VSCE AND MFTF WITH 120% FLOW ENTRAINMENT MIXER EJECTOR NOZZLES ACHIEVE SIDELINE NOISE GOAL**
- **TBE WITH INLET FLOW VALVE AND 43% NOZZLE FLOW ENTRAINMENT ACHIEVES SIDELINE NOISE GOAL**
- **TBE PROVIDES LOWER TOGW THAN VSCE (12% FOR M 2.4, 14% FOR M 3.2)**
- **TBE TOGW IS COMPETITIVE WITH MFTF FOR MACH 3.2**
- **MACH 2.4 TBE, MFTF ENGINES AND MIXER/EJECTOR NOZZLES ARE CURRENTLY BEING DEFINED AND EVALUATED USING COMMON GEAE/P&W GROUND RULES**

Figure 26

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